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# MODELING OF LOW-FIELD MAGNETIC STIMULATION OF THE HUMAN BRAIN

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## ABSTRACT

The World Health Organization reports psychological depression to become the second leading cause of disability worldwide after the heart disease by 2020, affecting all ages and both sexes. Today the depression treatment market amounts to billions of dollars and shows substantial growth over the last decade. The purpose of this paper is to introduce the ongoing research devoted to the investigation of a possibility to use low-field electromagnetic stimulation of the human brain in the treatment of depressive disorder. On the first stage, 3D models of transcranial magnetic stimulation and low-field magnetic stimulation based upon the use of a layered sphere head model have been developed. The modeling has shown that the coils are capable of inducing a current density in the order of 0.1 mA/m$^2$ for 30 mm deep into the head. Knowing the order of a stimulating electromagnetic field in LFMS model, it is possible to initiate drafting of a technical specification for the stimulator device.

***Index Terms –*** depression treatment, TMS, LFMS, electromagnetic modeling

## 1. INTRODUCTION

The motivation for our ongoing research comes from the reports of the World Health Organization, projecting psychological depressive disorders to become the second leading cause of disability worldwide after the heart disease by the year of 2020, affecting all ages and both sexes [1]. A literature review reveals low-field magnetic stimulation (LFMS) of the human brain as an under-researched area [2]. Based on the proven influence of low electromagnetic fields on biological cells [3], but taking into an account disputes regarding effects of an exposure to LFMS for complex systems, the objective of the work is to investigate whether LFMS is suitable for the treatment of depressive disorders.

The nature of depressive disorder is characterized by a situation in which a person cannot help himself and a medical intervention is needed. It is important to notice that we are referring not only to clinical cases of major depression classified in ICD-10, but often to mood disorders in general. The depression treatment market has substantial annual growth over the last decade and today it amounts to billions of dollars [4]. Among the variety of available means to defeat depression, the most commonly used forms of treatment nowadays are psychotherapy, antidepressants, and a recently adopted transcranial magnetic stimulation (TMS). Antidepressant medication may have adverse side effects and the TMS as a complex multipurpose system has disadvantages like cost and clinical use only. Therefore, we propose to implement LFMS in a hand-held stimulator as an inexpensive competitor suitable for easy and safe home use.

Non-invasive navigated TMS systems present the current state-of-the-art in tools for depression treatment [5]. While TMS and LFMS share the same physical phenomena, the medical phenomena may vary and are still under investigation. Wide range of information regarding TMS is available in the public domain, but so far there are no 3D electromagnetic models of LFMS existing.

## 2. MATERIALS AND METHODS

The research project consists of three main stages. Stage one refers to the development of a theoretical background of the investigated problem. It is done by means of 3D electromagnetic modeling of LFMS, where a layered sphere human head model is used initially. The outcome of the first stage is a technical specification for the experimental stimulator device. Stage two refers to the design of a device implementing our approach: hardware, software, and coil set. Stage three refers to clinical trials on human volunteers aiming to verify whether the use of the proposed LFMS, implemented in a developed stimulator, is suitable for depression treatment. We intend to use heart rate variability as an established indicator of the depression severity [6]. This paper describes the realization of the first stage, which goal is to develop the LFMS model.

The theory behind the electromagnetic stimulation of excitable human tissue is represented by three key elements, which are: resonant circuits, electromagnetic field theory, and finite element analysis. We are dealing with the transient analysis of the quasi-static problems in 3D. These problems are the most complex and resource demanding among all of the problems in electromagnetic computer modeling.

### 2.1. Electromagnetic theory

Resonant electric circuits are able to produce differently dumped output current waveforms which are called monophasic, biphasic, or polyphasic excitation signals in terms of stimulator devices. An ordinary TMS stimulator in Figure 1 works as follows: a kV source is charging a mF capacitor and when charging is completed, it is rapidly discharging onto the stimulating coil, which creates a very strong electromagnetic field for some microseconds.

The fundamental theoretical basis of both TMS and LFMS is the Maxwell's classical electromagnetic theory. According to Ampere's law, an alternating current flowing in the coil produces a time-varying magnetic field (1). In agreement with Faraday's law this magnetic field subsequently generates a time-varying electric field (2) represented as eddy currents induced in the head, as it follows from Ohm's law (3). That gives tissue excitation by depolarization of neurons via current flow through cell membranes.

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \quad (1)$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (2)$$

$$\vec{J} = \sigma \vec{E} \quad (3)$$

$$\vec{n} \times \vec{A} = 0 \quad (4)$$

$$\vec{n} \times \left( \vec{H}_1 - \vec{H}_2 \right) = 0 \quad (5)$$

$$\sigma \frac{\partial \vec{A}}{\partial t} + \nabla \times \left( \frac{\nabla \times \vec{A}}{\mu \mu_0} \right) = \vec{J} \quad (6)$$

$$\vec{B} = \nabla \times \vec{A} \quad (7)$$

$$\vec{E} = -\frac{\partial \vec{A}}{\partial t} - \nabla V \quad (8)$$

$$\vec{B}(\vec{r}, t) = I(t) \frac{\mu_0}{4\pi} \oint_{coil} \frac{(\vec{r} - \vec{r}_0)}{\left| \vec{r} - \vec{r}_0 \right|^3} \times d\vec{l} \quad (9)$$

In the finite element method the modeling of all of these interactions is done by the use of either A-V or T-Ω formulations, where *A* is the magnetic vector potential, *V* the electric scalar potential, *T* the current vector potential, and *Ω* the magnetic scalar potential. However, T-Ω formulation is not designated for the calculation of an electric field coming from a time-varying magnetic field produced by a stranded conductor. Considering all of the necessary boundary conditions – usually the Dirichlet condition (4) of magnetic insulation on the external boundary and the Neumann condition (5) of continuity on all of the internal boundaries – a large system of linear equations similar to (6) given for every mesh node is solved for the magnetic vector potential. Later, the magnetic field (7) and the electric field (8) can be calculated from the known magnetic vector potential.

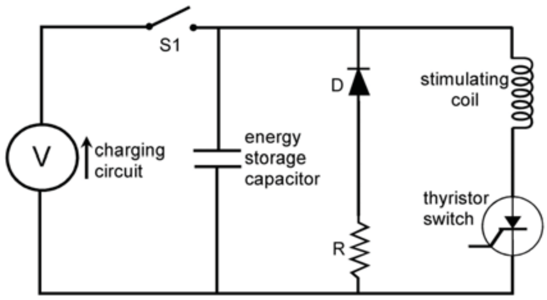


*Figure 1. Schematic of magnetic stimulator from [5]*

### 2.2. Electromagnetic modeling

The analytical solution for this time-dependent problem by means of Biot-Savart law (9) was not trivial. Therefore, we employed 3D finite element analysis software to conduct the actual modeling. Since the software development was not a part of our research, we decided to use the well-known publically available one – Ansoft Maxwell (T-Ω formulation) and COMSOL Multiphysics (A-V formulation).

The LFMS and TMS models were based upon the use of the layered sphere model of the human head with the radius of 10 cm, where skin, skull, cerebrospinal fluid (CSF), and brain tissues were represented as homogeneous spheres of different diameter, concentrically embedded one inside the other. The electrical conductivity σ, the dielectric permittivity ε, and the magnetic permeability μ of human tissues were taken from [7]. The rough values for the main tissues were given in the Table 1 for the frequency of 1 kHz. The electromagnetic properties of the brain were estimated as a mean value between those of white and gray matter.

*Table 1. Relevant properties of human head tissues*

| Tissue | Conductivity, S/m | Permittivity |
|---|---|---|
| Skin | 0.00066 | 32,000 |
| Skull | 0.02 | 2700 |
| CSF | 2 | 110 |
| Brain | 0.081 | 117,000 |

We did the modeling by means of commonly used techniques [8–9]. For the initial experiments with the modeling of LFMS we decided to use 8 small Coilcraft 684B coils at the sites typical for depression treatment, i. e. frontal lobe and temporal lobes. Two sets of 4 coils were placed at each side of the head and arranged around the points of F3 and F4 according to the international 10-20 system. A sine wave current with a peak value of 1 A at a frequency of 1 kHz was used for excitation. TMS was modeled with the two most frequently used coil types: flat circular coil with the average diameter of 10 cm and figure-of-eight coil, average diameter of 5 cm each loop. A 1 ms long monophasic pulse with the peak of 6.2 kA at 130 μs was chosen as excitation current.

Whereas the fairly low frequency range used in LFMS usually causes a deep penetration depth, the studied weak fields mitigated that effect. Hence, the induced currents penetrated only a rather small depth within the head. This allowed us to consider only the eighth part of the layered sphere head model – the upper left frontal part of the head with the point of F4 shown in Figure 4. In turn, the use of only one-eighth part of the head allowed fine meshing, so that obtained model of LFMS became very precise.

### 2.3. Stimulator development

The main issue of the stimulator development is the generation of the excitation current signal, which is controlled and triggered by a microcontroller (μC) shown in Figure 2. Using the LCD screen placed on the front side of the device, it is possible to set appropriate stimulation frequency for the intended application of depression treatment. The implemented frequency range varies from 30 Hz up to 1 kHz. Currently only sinusoidal oscillations can be created. Each sine wave is represented as a dataset consisted of 40 points. Two microcontrollers with internal two-channel digital-to-analog converters (DAC) are shaping the analog signal. Every channel has a phase shift of 90 degrees in comparison to the previous channel. The power supply current equals to 200 mA. To drive the 680 μH coils we need amplifiers at the outputs. For each channel we have used a 3 W mono audio amplifier module.

## 3. RESULTS

In the course of the first stage of work, we developed and debugged the 3D models of transcranial magnetic stimulation and low-field magnetic stimulation, based upon the use of a layered sphere head model. These models, reflecting the quantity of main interest – distribution of induced current density |***J***| inside the brain sphere, represented in Figure 3 and Figure 4, respectively. For both cases, peak values of the current density induced inside the human head were registered in CSF as roughly 1 mA/m$^2$ for LFMS and 160 A/m$^2$ for TMS. It was explained by a conductivity of CSF which was high in a comparison to other head tissues in Table 1.

As the model of TMS was used for auxiliary purposes, it consisted of around 40,000 linear tetrahedral mesh elements and was calculated on a workstation computer. The modeled electromagnetic fields coincided with the results of other's experiments by showing that for the figure-of-eight coil stimulation occurred under its center and for the flat circular coil – under its circumference. Magnetic flux density |***B***| of 2.7 T were measured 5 mm below the coil surface at the intersection of the loops, and only of 1.8 T at the centers of the loops.

The model of LFMS was made precise. It consisted of approximately 30,000 tetrahedrons with quadratic shape functions, amounted to 220,000 degrees of freedom, and was calculated on the local computer cluster. The modeling showed that the coils were capable of generating a peak magnetic flux density |***B***| of 66 mT within the core, what corresponded to the electric field |***E***| of 41 mV/m inside the head. A current density |***J***| in the order of 0.1 mA/m$^2$ was induced up to 30 mm deep into the head along the main stimulation axis, i. e. the line drawn from the point of F4 on the head surface to the center of the head matched with the origin of the coordinates.

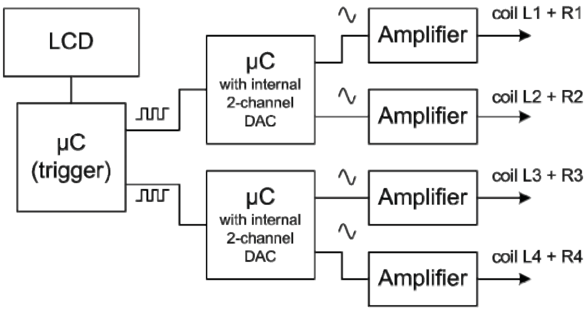


*Figure 2. Principal scheme of the stimulator*

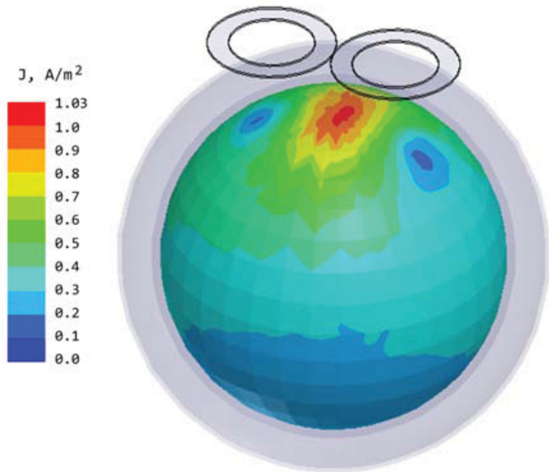


*Figure 3. Model of transcranial magnetic stimulation*

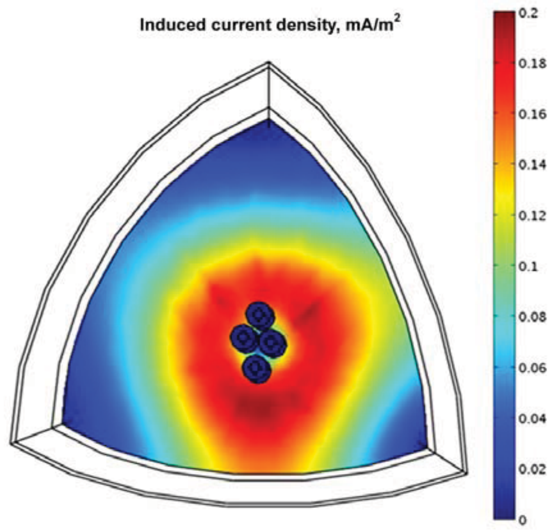


*Figure 4. Model of low-field magnetic stimulation*

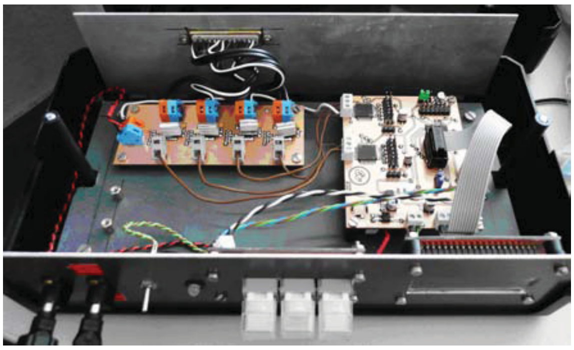

*Figure 5. Prototype of the stimulator*

## 4. DISCUSSION

With the help of the obtained models we are able to determine the relationships between the currents induced inside the human brain and an excitation current placed in a particular kind of the coil set. Knowing the order of a stimulating electromagnetic field in LFMS model, it is possible to initiate drafting of a technical specification for the stimulation device. This information is used for the development of the stimulator prototype, shown in Figure 5. To reveal the real parameters of the stimulation, a more extensive inverse "model-prototype" study is needed. We are planning a validation of LFMS modeling against the field measurements within a human head saline water phantom by means of the stimulator prototype.

## 5. CONCLUSION

We can conclude that the treatment of depression and related disorders is an important topic to work on. Application of low-intensity electromagnetic fields in this area is under-researched. We have developed the 3D electromagnetic models of both TMS and LFMS. The results of our study have been successfully compared to the literature. Now we are working under the development of a realistic head model, based on MRI and CT scans of a human head [10] and designed to replace the layered sphere model. With this work we are starting the evaluation of LFMS as a novel technique suitable for the treatment of depression and other neuropsychological disorders having origins similar to those of depression.

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